

Charm Phenomenology for CKM Parameters

Alexey A. Petrov

Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA

We review several key aspects of charm phenomenology which are important for the general program of determination of matrix elements of the Cabbibo-Kobayashi-Maskawa (CKM) matrix. We argue that charm physics plays an important role in reducing uncertainties in non-perturbative QCD parameters whose values are required for understanding of underlying quark-level processes. We also review the current status of searches for new physics in mixing and CP violation in charmed mesons both at the currently operating and proposed facilities.

1 Introduction

Charm physics plays a unique dual role in the modern investigation of flavor physics. Charm decay and production experiments provide valuable checks and supporting measurements for studies of CP -violation in measurements of CKM parameters in b -physics, as well as outstanding opportunities for searches for new physics.

Historically, many methods of heavy quark physics have been first tested in charmed hadrons. The fact that a b -quark mainly decays into a charm quark makes charm physics an integral part of any b -physics program. As we shall see in many cases, direct measurements of charm decay parameters directly affect the studies of fundamental physics in B decays.

Any search for new physics falls into two distinct categories: *direct*, when new physics particles are directly produced in the experiment and *indirect*, when they only affect low energy observables via quantum corrections. In turn, indirect searches can also be roughly divided into three classes, depending on which observables or processes are used in the search: 1) Processes forbidden in the Standard Model (SM), i.e. absent at any order in expansion in any of the coupling constants of SM. An example of those could be provided by charge-violating transitions $B^+ \rightarrow \mu^+\mu^-$ or $D^0 \rightarrow \mu^+\mu^+$. 2) Processes forbidden in the Standard Model at tree level, but possible at higher orders. Examples of those processes involve flavor-changing neutral current (FCNC) transitions, such as familiar $B \rightarrow X_{d,s}\gamma$, $D \rightarrow X_u\gamma$ or $B^0 - \bar{B}^0/D^0 - \bar{D}^0$ mixing. 3) Processes allowed in the Standard Model. Examples of the tests that belong to this category include examinations of the relations between different observables that are satisfied in the Standard Model, but not necessary in general. An example of those are the triangle relations among CKM parameters extracted from several different decays.

The Standard Model is a very constrained system, which implements a remarkably simple and economic description of all CP -violating processes in the flavor sector by a

single CP -violating parameter, the phase of the CKM matrix. This fact relates all CP -violating observables in bottom, charm and strange systems and provides an excellent opportunity for searches of physics beyond the Standard Model.

2 Supporting B-physics measurements

One of the major goals of the contemporary experimental B physics program is an accurate determination of the CKM parameters. As we shall see below, inputs from charm decays are important ingredient in this program, both in the extraction of the angles and sides of the CKM unitarity triangle.

2.1 Extraction of the CKM angle γ

Some of the cleanest methods of the determination of the CKM phase $\gamma = \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$ involve the interference of the $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ quark-level transitions [1, 2]. A way to arrange for an interference of those seemingly different processes was first pointed out in [3]. It involves interference of two *hadronic* decays $B^+ \rightarrow D^0K^+ \rightarrow fK^+$ and $B^+ \rightarrow \bar{D}^0K^+ \rightarrow fK^+$, with f being any common final state for D^0 and \bar{D}^0 decays. Since then, many different methods have been proposed, mainly differing by the fK final state and paths of reaching it: a combination of the Cabibbo-favored (CF) and doubly-Cabibbo suppressed decays (DCSD) $D^0(\bar{D}^0) \rightarrow K^+\pi^-$ [4], singly-Cabibbo suppressed decays (SCSD) $D^0(\bar{D}^0) \rightarrow KK^*$ [5], Cabibbo-favored decays employing large $K^0 - \bar{K}^0$ mixing $D^0(\bar{D}^0) \rightarrow K_S\pi^0$ [6], as well as multibody versions of these transitions [7]. For similar methods involving interference of the *initial* state, see [8].

Each of those methods involve observations of several B decay modes, so all of the hadronic unknowns, such as the ratio

$$A(B^+ \rightarrow D^0K^+)/A(B^+ \rightarrow \bar{D}^0K^+) = r_B e^{i(\gamma+\Delta_B)}, \quad (1)$$

or $A(D^0 \rightarrow f)/A(\bar{D}^0 \rightarrow f)$, as well as γ , can be determined from the B -decay measurements only. Yet, all of those methods will benefit from the separately performed charm decay measurements, the primary reason being the need for large statistics in any experimental determination of γ . For example, an ADS method [4] employs a ratio of a DCS to CF decays $A(D^0 \rightarrow K^+\pi^-)/A(\bar{D}^0 \rightarrow K^+\pi^-) = r_D e^{i\delta_D}$. The accuracy of this method will be greatly improved if r_D and δ_D are measured separately. While the separate measurement of r_D is already available, determination of δ_D will become possible at the upcoming tau-charm factories (TCF) at Cornell (CLEO-c) and Beijing (BES-III).

The basic idea is to make use of an important experimental advantage of TCF: operation at the $D^0\bar{D}^0$ threshold, where the D^0 and \bar{D}^0 are produced in the quantum-mechanically coherent initial state [9, 10]. Since the initial $D^0\bar{D}^0$ state is prepared as

$$|D\bar{D}^0\rangle_L = \frac{1}{\sqrt{2}} \left\{ |D^0(k_1)\bar{D}^0(k_2)\rangle + (-1)^L |D^0(k_2)\bar{D}^0(k_1)\rangle \right\}, \quad (2)$$

where L is the relative angular momentum of two D mesons, CP properties of the final states produced in the decay of $\psi(3770)$ are anti-correlated, one D state decayed into the final state with definite CP properties immediately identifies or tags CP properties of the state “on the other side.” That is to say, if one state decayed into, say $\pi^0 K_S$ with $CP = -1$, the other state is “CP-tagged” as being in the $CP = +1$ state. This allows one to measure $\cos \delta_D$. In order to see this, let us write a triangle relation,

$$\sqrt{2}A(D_\pm \rightarrow K^-\pi^+) = A(D^0 \rightarrow K^-\pi^+) \pm A(\bar{D}^0 \rightarrow K^-\pi^+), \quad (3)$$

which follows from the fact that, in the absence of CP-violation in charm, mass eigenstates of the neutral D meson coincide with its CP-eigenstates,

$$\sqrt{2}|D_\pm\rangle = |D^0\rangle \pm |\bar{D}^0\rangle. \quad (4)$$

This implies a relation for the branching ratios,

$$1 \pm 2 \cos \delta_D \sqrt{r_D} = 2 \frac{Br(D_\pm \rightarrow K^-\pi^+)}{Br(D^0 \rightarrow K^-\pi^+)}, \quad (5)$$

where we used the fact that $r_D \ll \sqrt{r_D}$ and neglected CP violation in mixing, which could undermine the CP-tagging procedure by splitting the CP-tagged state on one side into a linear combination of CP-even and CP-odd states. Its effect, however, is completely negligible here. Now, if both decays of D_+ and D_- are measured, $\cos \delta_D$ can be obtained from the asymmetry

$$\cos \delta_D = \frac{Br(D_+ \rightarrow K^-\pi^+) - Br(D_- \rightarrow K^-\pi^+)}{2\sqrt{r_D} Br(D^0 \rightarrow K^-\pi^+)}. \quad (6)$$

Both Eqs. (5) and (6) can be used to extract δ_D at TCF. Similar measurements are possible for other D decays [11].

In addition, some methods require cross-checks in the charm sector that might restrict the accuracy of these methods. A good example is provided by the original GW method [3], which does not take into account the possibility of relatively large $D^0 - \bar{D}^0$ mixing [9]. This method relies on the simple triangle amplitude relation $\sqrt{2}A(B^+ \rightarrow D_\pm K^+) = A(B^+ \rightarrow D^0 K^+) \pm A(B^+ \rightarrow \bar{D}^0 K^+)$, again provided by Eq. (4). An amplitude $A(B^+ \rightarrow D_\pm K^+)$ is measured with D decaying to a particular CP-eigenstate. Neglecting $D^0 - \bar{D}^0$ mixing, angle γ can then be extracted, up to a discrete ambiguity, from the measurements of $B^\pm \rightarrow f_{CP} K^\pm$ and $B^\pm \rightarrow D^0, \bar{D}^0 K^\pm$. In particular,

$$\Gamma[B^\pm \rightarrow f_{CP} K^\pm] \propto 1 + r_B^2 + 2r_B c_\pm, \quad (7)$$

where $c_\pm = \cos(\gamma \pm \Delta_B)$ and r_B and Δ_B are defined from the ratio Eq. (1). Then,

$$\sin^2 \gamma = \frac{1}{2} \left[1 - c_+ c_- \pm \sqrt{(1 - c_+^2)(1 - c_-^2)} \right]. \quad (8)$$

It is easy to see that $D^0 - \bar{D}^0$ mixing, if not properly accounted for, can affect the results of this analysis. Indeed, taking $D^0 - \bar{D}^0$ mixing into account results in the modification of the definitions of c_\pm ,

$$\begin{aligned} c_\pm &\rightarrow \cos(\gamma \pm \Delta_B) \mp \frac{x}{2r_B} \sin 2\theta_D \\ &- \frac{y}{2r_D} \left[2\eta_f r_D \cos(\gamma + 2\theta_D \pm \Delta_B) + \cos 2\theta_D \right], \end{aligned} \quad (9)$$

where

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \quad (10)$$

with $m_{1,2}$ and $\Gamma_{1,2}$ being the masses and widths of D -meson mass eigenstates $D_{1,2}$, η_f is a CP-parity of f_{CP} , and θ_D is a CP-violating phase of $D^0 - \bar{D}^0$ mixing. It is easy to see that $y \sim 1\%$ can impact the determination of γ from these modes. Thus, separately constraining $D^0 - \bar{D}^0$ mixing parameters will be helpful. We shall discuss those later.

2.2 Cross-checks of unitarity relations

There are several unitarity triangles that involve charm inputs [12]. Since all CP-violating effects in the flavor sector of the SM are related to the single phase of the CKM matrix, all of the CKM unitarity triangles, including the ones with most charm inputs, have the same area. This could provide a non-trivial check of the Standard Model, if measurements of all sides of these triangles are measured with sufficient accuracy. Unfortunately, “charm triangles” are “squashed”, with one side being much shorter than the

other two. For example, in terms of the Wolfenstein parameter $\lambda = 0.22$, the relation $V_{td}V_{cd}^* + V_{ts}V_{cs}^* + V_{tb}V_{cb}^* = 0$ has one side $O(\lambda^4)$ with the other two being $O(\lambda^2)$, while the relations $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$ and $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$ have one side $O(\lambda^5)$ with the other two being $O(\lambda)$. Even though the second relation could provide an interesting information about the top quark CKM parameters and the last one can be checked using only the tree-level transitions, it is unlikely that the required accuracy will be achieved in the near future.

In addition, tests similar to the “first row unitarity”, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ (which at the moment fails at the level of 2.2σ [13]) are possible. For example, $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$. It could provide an interesting cross-check on the value of V_{cb} extracted in B-decays, if sufficient accuracy on the experimental measurement of V_{cd} and V_{cs} is achieved.

2.3 Form-factors and decay constants

Since $m_b, m_c \gg \Lambda_{QCD}$, both charm and bottom quarks can be regarded as heavy quarks. Naturally, heavy quark symmetry relates observables in B and D transitions. As an example, let us consider measurements in the charm sector affect determinations of the CKM matrix elements relevant to top quark in $B^0 - \bar{B}^0$ mixing.

A mass difference of mass eigenstates in $B^0 - \bar{B}^0$ system can be written as

$$\Delta m_d = C \left[\alpha_s^{(5)}(\mu) \right]^{-6/23} \left[1 + \frac{\alpha_s^{(5)}(\mu)}{4\pi} J_5 \right] \langle \bar{B}_d^0 | O(\mu) | B_d^0 \rangle, \quad (11)$$

where $C = G_F^2 M_W^2 (V_{tb}^* V_{td})^2 \eta_B m_B S_0(x_t) / (4\pi^2)$ (see Ref. [14] for complete definitions of the parameters in this expression). The largest uncertainty of about 30% in the theoretical calculation is introduced by the poorly known hadronic matrix element $A = \langle \bar{B}^0 | O(\mu) | B^0 \rangle$. Evaluation of this matrix element is a genuine non-perturbative task, which can be approached with several different techniques. The simplest approach (“factorization”) reduces the matrix element A to the product of matrix elements measured in leptonic B decays $A^f = (8/3) \langle \bar{B}^0 | \bar{b}_L \gamma_\sigma d_L | 0 \rangle \langle 0 | \bar{b}_L \gamma^\sigma d_L | B^0 \rangle = (2/3) f_B^2 m_B^2$, where we employed the definition of the decay constant f_B ,

$$\langle 0 | \bar{b}_L \gamma_\mu d_L | B^0(\mathbf{p}) \rangle = i p_\mu f_B / 2. \quad (12)$$

A deviation from the factorization ansatz is usually described by the parameter B_{B_d} defined as $A = B_{B_d} A^f$; in factorization $B_{B_d} = 1$. Similar considerations lead to an introduction of the parameter B_{B_s} defined for mixing of B_s mesons. It is important to note that the parameters B_{B_q} depend on the chosen renormalization scale and scheme. It

Table 1. Renormalization-group independent B-parameters.

Method (reference)	\hat{B}_{B_d}	$\hat{B}_{B_s} / \hat{B}_{B_d}$
Lattice, '03 [15]	1.34(12)	1.00(3)
QCDSR, '03 [15]	1.67 ± 0.23	≈ 1
Lattice, '03 [16]	$1.277(88)^{(+86)}_{(-95)}$	$1.017(16)^{(+56)}_{(-17)}$
QCDSR, '03 [17]	1.60 ± 0.03	≈ 1

is convenient to introduce renormalization-group invariant parameters \hat{B}_{B_q}

$$\hat{B}_{B_q} = \left[\alpha_s^{(5)}(\mu) \right]^{-6/23} \left[1 + \frac{\alpha_s^{(5)}(\mu)}{4\pi} J_5 \right] B_{B_q}. \quad (13)$$

We provide averages of \hat{B}_{B_q} , as well as the ratio $\hat{B}_{B_s} / \hat{B}_{B_d}$ from the review [15] as well as from two more recent evaluations [16, 17] in Table 1. Thus, at least naively, one can determine CKM matrix element V_{td} by measuring f_B and Δm_d and computing B_{B_q} .

This direct approach, however, meets several difficulties. First, leptonic decay constant f_B can in principle be extracted from leptonic decays of charged B mesons. The corresponding decay width is

$$\Gamma(B \rightarrow lv) = \frac{G_F^2}{8\pi} f_B^2 |V_{ub}|^2 m_l^2 m_B \left(1 - \frac{m_l^2}{m_B^2} \right). \quad (14)$$

This width is seen to be quite small due to the smallness of the CKM factor $|V_{ub}|$ and helicity suppression factor of m_l^2 . In addition, experimental difficulties are also expected due to the backgrounds stemming from the presence of a neutrino in the final state.

Second, computation of B_{B_q} is quite difficult and requires the use of non-perturbative techniques such as lattice or QCD Sum Rules. Current uncertainties in the determinations of f_B and B_{B_q} are quite large. It turns out that evaluation of the ratio of

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \left[\frac{\sqrt{B_{B_d} f_{B_d}}}{\sqrt{B_{B_s} f_{B_s}}} \right]^2 \left| \frac{V_{td}}{V_{ts}} \right|^2, \quad (15)$$

is favored by lattice community, as many systematic errors cancel in this ratio. This gives a ratio of $|V_{td}/V_{ts}|$, which provides a non-trivial constraint on CKM parameters in the $\rho - \eta$ plane.

Instead, one can make use of ample statistics available in charm production experiments, as heavy quark and $SU(3)$ flavor symmetries relate the ratio of charm decay constants f_{D_s}/f_D to beauty decay constants f_{B_s}/f_B

$$\frac{f_{B_s}/f_B}{f_{D_s}/f_D} = 1 + O(m_s) \times O(1/m_b - 1/m_c). \quad (16)$$

Note that SU(3)-violating corrections can also be evaluated in chiral perturbation theory [18]. One still needs to rely on the theoretical determination of B_{B_q} .

Similar techniques of relating B and D decays can also be used to extract other CKM matrix elements, like V_{ub} [19], studies of lifetime patterns of heavy hadrons [20], and tuning lattice QCD calculations [21].

3 Searching for New Physics

Another area of modern phenomenology where charm decays play an important role is the indirect search for physics beyond the Standard Model. Indeed, large statistics usually available in charm physics experiment makes it possible to probe small effects that might be generated by the presence of new physics particles and interactions. A program of searches for new physics in charm is complementary to the corresponding programs in bottom or strange systems. This is in part due to the fact loop-dominated processes such as $D^0 - \bar{D}^0$ mixing or flavor-changing neutral current (FCNC) decays are sensitive to the dynamics of ultra-heavy *down-type particles*. Also, in many dynamical models, including the Standard Model, the effects in s , c , and b systems are correlated.

The low energy effect of new physics particles can be naturally written in terms of a series of local operators of increasing dimension generating $\Delta C = 1$ (decays) or $\Delta C = 2$ (mixing) transitions. For $D^0 - \bar{D}^0$ mixing these operators, as well as the one loop Standard Model effects, generate contributions to the effective operators that change D^0 state into \bar{D}^0 state leading to the mass eigenstates

$$|D_2\rangle = p|D^0\rangle + q|\bar{D}^0\rangle, \quad (17)$$

where the complex parameters p and q are obtained from diagonalizing the $D^0 - \bar{D}^0$ mass matrix. The mass and width splittings between these eigenstates are given in Eq. (10). It is known experimentally that $D^0 - \bar{D}^0$ mixing proceeds extremely slowly, which in the Standard Model is usually attributed to the absence of superheavy quarks destroying GIM cancellations [22].

It is instructive to see how new physics can affect charm mixing. Since the lifetime difference y is constructed from the decays of D into physical states, it should be dominated by the Standard Model contributions, unless new physics significantly modifies $\Delta C = 1$ interactions. On the contrary, the mass difference x can receive contributions from all energy scales. Thus, it is usually conjectured that new physics can significantly modify x leading to the inequality $x \gg y$ ¹.

¹This signal for new physics is lost if a relatively large y , of the order of a percent, is observed [23, 24].

The same considerations apply to FCNC decays as well, where new physics could possibly contribute to the decay rates of $D \rightarrow X_u \gamma$, $D \rightarrow X_u l^+ l^-$ (with X_u being exclusive or inclusive final state) as well as other observables [25]. One technical problem here is that in the standard model these decays are overwhelmingly dominated by long-distance effects, which makes them extremely difficult to predict model-independently. This problem can be turned into a virtue [26].

Another possible manifestation of new physics interactions in the charm system is associated with the observation of (large) CP-violation. This is due to the fact that all quarks that build up the hadronic states in weak decays of charm mesons belong to the first two generations. Since 2×2 Cabbibo quark mixing matrix is real, no CP-violation is possible in the dominant tree-level diagrams that describe the decay amplitudes. In the Standard Model CP-violating amplitudes can be introduced by including penguin or box operators induced by virtual b -quarks. However, their contributions are strongly suppressed by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$. It is thus widely believed that the observation of (large) CP violation in charm decays or mixing would be an unambiguous sign for new physics. This fact makes charm decays a valuable tool in searching for new physics, since the statistics available in charm physics experiment is usually quite large.

As in B-physics, CP-violating contributions in charm can be generally classified by three different categories: (I) CP violation in the decay amplitudes. This type of CP violation occurs when the absolute value of the decay amplitude for D to decay to a final state f (A_f) is different from the one of corresponding CP-conjugated amplitude (“direct CP-violation”); (II) CP violation in $D^0 - \bar{D}^0$ mixing matrix. This type of CP violation is manifest when $R_m^2 = |p/q|^2 = (2M_{12} - i\Gamma_{12})/(2M_{12}^* - i\Gamma_{12}^*) \neq 1$; and (III) CP violation in the interference of decays with and without mixing. This type of CP violation is possible for a subset of final states to which both D^0 and \bar{D}^0 can decay.

For a given final state f , CP violating contributions can be summarized in the parameter

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} = R_m e^{i(\phi+\delta)} \left| \frac{\bar{A}_f}{A_f} \right|, \quad (18)$$

where A_f and \bar{A}_f are the amplitudes for $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow f$ transitions respectively and δ is the strong phase difference between A_f and \bar{A}_f . Here ϕ represents the convention-independent weak phase difference between the ratio of decay amplitudes and the mixing matrix.

3.1 $D^0 - \bar{D}^0$ mixing parameters

Presently, experimental information about the $D^0 - \bar{D}^0$ mixing parameters x and y comes from the time-dependent

analyses that can roughly be divided into two categories. First, more traditional studies look at the time dependence of $D \rightarrow f$ decays, where f is the final state that can be used to tag the flavor of the decayed meson. The most popular is the non-leptonic doubly Cabibbo suppressed decay $D^0 \rightarrow K^+\pi^-$. Time-dependent studies allow one to separate the DCSD from the mixing contribution $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$,

$$\Gamma[D^0(t) \rightarrow K^+\pi^-] = e^{-\Gamma t} |A_{K^+\pi^-}|^2 \times \left[R + \sqrt{R} R_m (y' \cos \phi - x' \sin \phi) \Gamma t + \frac{R_m^2}{4} (y^2 + x^2) (\Gamma t)^2 \right], \quad (19)$$

where R is the ratio of DCS and Cabibbo favored (CF) decay rates. Since x and y are small, the best constraint comes from the linear terms in t that are also *linear* in x and y . A direct extraction of x and y from Eq. (19) is not possible due to unknown relative strong phase δ_D of DCS and CF amplitudes [27], as $x' = x \cos \delta_D + y \sin \delta_D$, $y' = y \cos \delta_D - x \sin \delta_D$. As discussed above, this phase can be measured independently [9, 10]. The corresponding formula can also be written [23] for \bar{D}^0 decay with $x' \rightarrow -x'$ and $R_m \rightarrow R_m^{-1}$.

Second, D^0 mixing can be measured by comparing the lifetimes extracted from the analysis of D decays into the CP-even and CP-odd final states. This study is also sensitive to a *linear* function of y via

$$\frac{\tau(D \rightarrow K^-\pi^+)}{\tau(D \rightarrow K^+K^-)} - 1 = y \cos \phi - x \sin \phi \left[\frac{R_m^2 - 1}{2} \right]. \quad (20)$$

Time-integrated studies of the semileptonic transitions are sensitive to the *quadratic* form $x^2 + y^2$ and at the moment are not competitive with the analyses discussed above.

The construction of new tau-charm factories CLEO-c and BES-III will introduce new *time-independent* methods that are sensitive to a linear function of y . One can again use the fact that heavy meson pairs produced in the decays of heavy quarkonium resonances have the useful property that the two mesons are in the CP-correlated states [28] (see Eq. (2)).

By tagging one of the mesons as a CP eigenstate, a lifetime difference may be determined by measuring the leptonic branching ratio of the other meson. Its semileptonic *width* should be independent of the CP quantum number since it is flavor specific, yet its *branching ratio* will be inversely proportional to the total width of that meson. Since we know whether this $D(k_2)$ state is tagged as a (CP-eigenstate) D_\pm from the decay of $D(k_1)$ to a final state S_σ of definite CP-parity $\sigma = \pm$, we can easily determine y in terms of the semileptonic branching ratios of D_\pm . This can be expressed simply by introducing the ratio

$$R_\sigma^L = \frac{\Gamma[\psi_L \rightarrow (H \rightarrow S_\sigma)(H \rightarrow X l^\pm \nu)]}{\Gamma[\psi_L \rightarrow (H \rightarrow S_\sigma)(H \rightarrow X)] Br(H^0 \rightarrow X l \nu)}, \quad (21)$$

where X in $H \rightarrow X$ stands for an inclusive set of all final states. A deviation from $R_\sigma^L = 1$ implies a lifetime difference. Keeping only the leading (linear) contributions due to mixing, y can be extracted from this experimentally obtained quantity,

$$y \cos \phi = (-1)^L \sigma \frac{R_\sigma^L - 1}{R_\sigma^L}. \quad (22)$$

The current experimental upper bounds on x and y are on the order of a few times 10^{-2} , and are expected to improve significantly in the coming years. To regard a future discovery of nonzero x or y as a signal for new physics, we would need high confidence that the Standard Model predictions lie well below the present limits. As was recently shown [24], in the Standard Model, x and y are generated only at second order in $SU(3)_F$ breaking,

$$x, y \sim \sin^2 \theta_C \times [SU(3) \text{ breaking}]^2, \quad (23)$$

where θ_C is the Cabibbo angle. Therefore, predicting the Standard Model values of x and y depends crucially on estimating the size of $SU(3)_F$ breaking. Although y is expected to be determined by the Standard Model processes, its value nevertheless affects significantly the sensitivity to new physics of experimental analyses of D mixing [23].

Theoretical predictions of x and y within and beyond the Standard Model span several orders of magnitude [29]. Roughly, there are two approaches, neither of which give very reliable results because m_c is in some sense intermediate between heavy and light. The “inclusive” approach is based on the operator product expansion (OPE). In the $m_c \gg \Lambda$ limit, where Λ is a scale characteristic of the strong interactions, ΔM and $\Delta \Gamma$ can be expanded in terms of matrix elements of local operators [30]. Such calculations yield $x, y < 10^{-3}$. The use of the OPE relies on local quark-hadron duality, and on Λ/m_c being small enough to allow a truncation of the series after the first few terms. The charm mass may not be large enough for these to be good approximations, especially for nonleptonic D decays. An observation of y of order 10^{-2} could be ascribed to a breakdown of the OPE or of duality, but such a large value of y is certainly not a generic prediction of OPE analyses. The “exclusive” approach sums over intermediate hadronic states, which may be modeled or fit to experimental data [31]. Since there are cancellations between states within a given $SU(3)$ multiplet, one needs to know the contribution of each state with high precision. However, the D is not light enough that its decays are dominated by a few final states. In the absence of sufficiently precise data on many decay rates and on strong phases, one is forced to use some assumptions. While most studies find $x, y < 10^{-3}$, Refs. [31] obtain x and y at the 10^{-2} level by arguing that $SU(3)_F$ violation is of order unity, but the source of the large $SU(3)_F$ breaking is not made explicit. It was

also shown that phase space effects alone provide enough $SU(3)_F$ violation to induce $y \sim 10^{-2}$ [24]. Large effects in y appear for decays close to D threshold, where an analytic expansion in $SU(3)_F$ violation is no longer possible. Thus, theoretical calculations of x and y are quite uncertain, and the values near the current experimental bounds cannot be ruled out. Therefore, it will be difficult to find a clear indication of physics beyond the Standard Model in $D^0 - \bar{D}^0$ mixing measurements alone. The only robust potential signal of new physics in charm system at this stage is CP violation.

3.2 CP-violation in charm

CP violation in D decays and mixing can be searched for by a variety of methods. For instance, time-dependent decay widths for $D \rightarrow K\pi$ are sensitive to CP violation in mixing (see Eq.(19)). Provided that the x and y are comparable to experimental sensitivities, a combined analysis of $D \rightarrow K\pi$ and $D \rightarrow KK$ can yield interesting constraints on CP-violating parameters [23].

Most of the techniques that are sensitive to CP violation make use of the decay asymmetry,

$$A_{CP}(f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})} = \frac{1 - |\bar{A}_{\bar{f}}/A_f|^2}{1 + |\bar{A}_{\bar{f}}/A_f|^2}. \quad (24)$$

Most of the properties of Eq. (24), such as dependence on the strong final state phases, are similar to the ones in B-physics [32]. Current experimental bounds from various experiments, all consistent with zero within experimental uncertainties, can be found in [33].

Other interesting signals of CP-violation that are being discussed in connection with tau-charm factory measurements are the ones that are using quantum coherence of the initial state. An example of this type of signal is a decay $(D^0 \bar{D}^0) \rightarrow f_1 f_2$ at $\psi(3770)$ with f_1 and f_2 being the different final CP-eigenstates of the same CP-parity. This type of signals are very easy to detect experimentally. The corresponding CP-violating decay rate for the final states f_1 and f_2 is

$$\begin{aligned} \Gamma_{f_1 f_2} &= \frac{1}{2R_m^2} \left[(2 + x^2 - y^2) |\lambda_{f_1} - \lambda_{f_2}|^2 \right. \\ &\quad \left. + (x^2 + y^2) |1 - \lambda_{f_1} \lambda_{f_2}|^2 \right] \Gamma_{f_1} \Gamma_{f_2}. \end{aligned} \quad (25)$$

The result of Eq. (25) represents a generalization of the formula given in Ref. [34]. It is clear that both terms in the numerator of Eq. (25) receive contributions from CP-violation of the type I and III, while the second term is also sensitive to CP-violation of the type II. Moreover, for a large set of the final states the first term would be additionally suppressed by $SU(3)_F$ symmetry, as for instance,

$\lambda_{\pi\pi} = \lambda_{KK}$ in the $SU(3)_F$ symmetry limit. This expression is of the *second* order in CP-violating parameters (it is easy to see that in the approximation where only CP violation in the mixing matrix is retained, $\Gamma_{f_1 f_2} \propto |1 - R_m^2|^2 \propto A_m^2$). As it follows from the existing experimental constraints on rate asymmetries, CP-violating phases are quite small in charm system, regardless of whether they are produced by the Standard Model mechanisms or by some new physics contributions. In that respect, it looks unlikely that the SM signals of CP violation would be observed at CLEO-c with this observable.

While the searches for direct CP violation via the asymmetry of Eq. (24) can be done with the charged D-mesons (which are self-tagging), investigations of the other two types of CP-violation require flavor tagging of the initial state. This severely cuts the available dataset. It is therefore interesting to look for signals of CP violation that do not require identification of the initial state. One possible CP-violating signal involves the observable obtained by summing over the initial states, $\sum \Gamma_i = \Gamma_i + \bar{\Gamma}_i$ for $i = f, \bar{f}$. A CP-odd observable that can be formed out of $\sum \Gamma_i$ is an asymmetry [35]

$$A_{CP}^U = \frac{\sum \Gamma_f - \sum \bar{\Gamma}_{\bar{f}}}{\sum \Gamma_f + \sum \bar{\Gamma}_{\bar{f}}}. \quad (26)$$

Note that this asymmetry does not require quantum coherence of the initial state and therefore is accessible in any D-physics experiment. The final states must be chosen such that A_{CP}^U is not trivially zero. It is easy to see that decays of D into the final states that are CP-eigenstates would result in zero asymmetry, while the final states like $K^+ K^{*-}$ or $K_S \pi^+ \pi^-$ would not. A non-zero value of A_{CP}^U in Eq. (26) can be generated by both direct and indirect CP-violating contributions. These can be separated by appropriately choosing the final states. For example, indirect CP violating amplitudes are tightly constrained in the decays dominated by the Cabibbo-favored tree level amplitudes, while singly Cabibbo suppressed amplitudes also receive contributions from direct CP violating amplitudes.

4 Acknowledgments

I would like to thank my collaborators as well as the organizers of this workshop for making it a success. This work was supported in part by the U.S. Department of Energy under grant DE-FG02-96ER41005.

References

1. R. Fleischer, these proceedings, arXiv:hep-ph/0306270.
2. T. J. Gershon, these proceedings, arXiv:hep-ex/0307020.

3. M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991).
4. D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997).
5. Y. Grossman, Z. Ligeti and A. Soffer, Phys. Rev. D **67**, 071301 (2003).
6. R. Fleischer, Nucl. Phys. B **659**, 321 (2003).
7. A. Giri, Y. Grossman, A. Soffer and J. Zupan, arXiv:hep-ph/0303187; J. Zupan, these proceedings; D. Atwood and A. Soni, these proceedings, arXiv:hep-ph/0307154.
8. A. F. Falk and A. A. Petrov, Phys. Rev. Lett. **85**, 252 (2000); A. F. Falk, Phys. Rev. D **64**, 093011 (2001).
9. J. P. Silva and A. Soffer, Phys. Rev. D **61**, 112001 (2000).
10. M. Gronau, Y. Grossman and J. L. Rosner, Phys. Lett. B **508**, 37 (2001); E. Golowich and S. Pakvasa, Phys. Lett. B **505**, 94 (2001).
11. J. L. Rosner and D. A. Suprun, arXiv:hep-ph/0303117.
12. I. I. Bigi and A. I. Sanda, arXiv:hep-ph/9909479.
13. H. Abele *et al.*, Phys. Rev. Lett. **88**, 211801 (2002).
14. G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996); A. J. Buras, M. Jamin and P. H. Weisz, Nucl. Phys. B **347**, 491 (1990); M. Ciuchini, E. Franco, G. Martinelli, L. Reina and L. Silvestrini, Z. Phys. C **68**, 239 (1995).
15. M. Battaglia *et al.*, arXiv:hep-ph/0304132.
16. S. Aoki *et al.* [JLQCD Collaboration], arXiv:hep-ph/0307039.
17. J. G. Korner, A. I. Onishchenko, A. A. Petrov and A. A. Pivovarov, arXiv:hep-ph/0306032.
18. B. Grinstein, Phys. Rev. Lett. **71**, 3067 (1993).
19. Z. Ligeti, I. W. Stewart and M. B. Wise, Phys. Lett. B **420**, 359 (1998).
20. D. Pedrini [the FOCUS Collaboration], these proceedings, arXiv:hep-ph/0307137; M. B. Voloshin, Phys. Rept. **320**, 275 (1999); B. Guberina, B. Melic and H. Stefancic, Phys. Lett. B **484**, 43 (2000).
21. P. Mackenzie, these proceedings; A. Juttner and J. Rolf, these proceedings, arXiv:hep-ph/0306299;
22. A. Datta, D. Kumbhakar, Z. Phys. C **27**, 515 (1985); A. A. Petrov, Phys. Rev. D **56**, 1685 (1997); E. Golowich and A. A. Petrov, Phys. Lett. B **427**, 172 (1998).
23. S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir, A. Petrov, Phys. Lett. B **486**, 418 (2000).
24. A. F. Falk, Y. Grossman, Z. Ligeti and A. A. Petrov, Phys. Rev. D **65**, 054034 (2002).
25. S. Fajfer, these proceedings, arXiv:hep-ph/0306263.
26. S. Fajfer, S. Prelovsek, P. Singer and D. Wyler, Phys. Lett. B **487**, 81 (2000).
27. A. F. Falk, Y. Nir and A. A. Petrov, JHEP **9912**, 019 (1999).
28. D. Atwood and A. A. Petrov, arXiv:hep-ph/0207165.
29. H. N. Nelson, in *Proc. of the 19th Intl. Symp. on Photon and Lepton Interactions at High Energy LP99* ed. J.A. Jaros and M.E. Peskin, arXiv:hep-ex/9908021.
30. H. Georgi, Phys. Lett. B **297**, 353 (1992); T. Ohl, G. Ricciardi and E. Simmons, Nucl. Phys. B **403**, 605 (1993); I. Bigi and N. Uraltsev, Nucl. Phys. B **592**, 92 (2001), for a recent review see A. A. Petrov, *Proc. of 4th Workshop on Continuous Advances in QCD*, Minneapolis, Minnesota, 12-14 May 2000, arXiv:hep-ph/0009160.
31. J. Donoghue, E. Golowich, B. Holstein and J. Trampetic, Phys. Rev. D **33**, 179 (1986); L. Wolfenstein, Phys. Lett. B **164**, 170 (1985); P. Colangelo, G. Nardulli and N. Paver, Phys. Lett. B **242**, 71 (1990); T.A. Kaeding, Phys. Lett. B **357**, 151 (1995). A. A. Anselm and Y. I. Azimov, Phys. Lett. B **85**, 72 (1979);
32. I. I. Bigi and A. I. Sanda, *CP violation* (Cambridge University Press, 2000).
33. D. Pedrini, J. Phys. G **27**, 1259 (2001).
34. I. I. Bigi and A. I. Sanda, Phys. Lett. B **171**, 320 (1986).
35. A. A. Petrov, *Proc. of the 5th Workshop on Continuous Advances in QCD*, pp. 102-114; arXiv:hep-ph/0209049.